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TECHNICAL REPORT
EP-82

WINDCHILL IN THE NORTHERN HEMISPHERE

QUARTERMASTER RESEARCH & ENGINEERING CENTER
ENVIRONMENTAL PROTECTION RESEARCH DIVISION

FEBRUARY 1958

NATICK, MASSACHUSETTS

HEADQUARTERS QUARTERMASTER RESEARCH & ENGINEERING COMMAND, US ARMY
Quartermaster Research & Engineering Center
Natick, Massachusetts

ENVIRONMENTAL PROTECTION RESEARCH DIVISION

Technical Report
EP-82

WINDCHILL IN THE NORTHERN HEMISPHERE

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FOREWORD

Quartermaster scientists are often concerned with problems of man's cold tolerance and the development of protective items which can extend his functional effectiveness under severe cold conditions. It is, therefore, necessary to know the global distribution of cold stress elements.

The accompanying study evolved from a need for a basic map reference on mean windchill occurrence for use in predicting distributions of various levels of soldier performance capabilities in cold environments. When windchill is related to performance of man and his equipment, a suitable map of the distribution of the soldier's responses or of item function capabilities can be derived.

This report presents for the first time a windchill map of the entire Northern Hemisphere.

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CONTENTS

ABSTRACT

Windchill is defined as the cooling power of wind and temperature combinations on shaded, dry human skin. It is measured in kilogram calories of heat loss per square meter of exposed skin surface per hour for each Centigrade degree of temperature difference between the skin and the ambient air.

The report points out the usefulness of the windchill index in assessing relative human comfort as well as its limitations with respect to evaporation and radiation influences. Tables simplifying computation of the index are included. These tables list temperature and wind speed factors derived from the windchill formula, converted from metric to English units for temperatures from 90°F. to -105°F. and for wind speeds from 0 to 45 miles per hour. Any pair of these factors applicable to a given situation may be multiplied directly to yield the windchill index.

A map of the Northern Hemisphere shows the mean win[illegible] distribution for the coldest mo[illegible] of the year, using isopleths a[illegible] [illegible]rvals of 100 units of win[illegible] [illegible]m 500 to 2,100 Kg.Cals./m^2/hr. [illegible]alues were derived f[illegible] [illegible] of temperature and wind speed [illegible]om more than 1,000 [illegible]

WINDCH[illegible] NORTHERN HEMISPH[illegible]

1. The Windchill Index

Development by [illegible]

The te[illegible] "windchill" was first introduce[illegible] Paul A. Siple as a te[illegible] describing relative discomfort [illegible] from combinations of wind [illegible] temperature. The windchill inde[illegible] originally developed, was [illegible] a multiplication of the wind [illegible] meters per second by the temperature in degrees Centigrade be[illegible] zero. This method was not applicable to temperatures above zero [illegible] degrees Centigrade, and had the additional disadvantage in that high wi[illegible] speed exaggerated the windchill values.

In 194[illegible] [illegible] new formula for [illegible] chill was developed by Siple and Passel(10) [illegible] experiments conducted [illegible] Little America, Antarctica. The form[illegible] given below, was related to observations of the freezing rate of water sealed in a plastic cylinder.

$$H = (\sqrt{100v} + 10.45 - v) (33 - t)$$

where H = Heat loss (Windchill) in Kg. Cals/[illegible]/hr.
v = Wind speed in meters per second
t = Air temperature in degrees Centigrade

The formula measures the cooling power of wind and temperature in complete shade, without regard to evaporation. The resulting heat loss is expressed in kilogram calories per square meter of exposed skin surface per hour.

Of the many formulas proposed by various investigators, Siple's is the only one based on actual observations in an extremely cold environment. Stone([illegible]), in a review of some windchill formulas, cautioned against extrapolation of formulas very far beyond the laboratory or experimental ranges over which they were originally evaluated. Siple's formula, moreover, has the advantage of having been evaluated over a lower temperature range (-9° to -56°C.) than the others.

Although windchill affords only a qualitative mea[illegible] of the cooling effect on the human body, it has been adopted as a descriptive value for the severity of cold environments. Burton and Edholm(3), in their text on the physiological and pathological effects of cold environments on man, state "The index of windchill has enjoyed a considerable, and deserved, popularity, for it has been proved in the field that it does indeed provide an index corresponding quite well with experience in the cold, [illegible], [illegible] the discomfort and tolerance of man in the cold".

[illegible]ations: Radiation, Evaporation, and Other Heat Losses

[illegible] the winter conditons existing during Siple's experiments in the [illegible]arctic, outgoing terrestrial radiation always exceeded incoming rad[illegible]ion. This avenue of heat loss, therefore, is included in the formu[illegible]. However, during periods of incoming radiation, whether direct or [illegible]fuse, the calculated values of windchill exceed the true values, since the formula does not consider this possible source of heat gain. Under conditions of bright sunshine the windchill index should be reduced by about 200 Kg.Cals/m^2/hr., and under light cloud conditions by about [illegible]0 Kg.Cals/m^2/hr. (see Section 3).

The windchill index is based upon a neutral skin temperature of 33°C. (91.4°F.). When body heat production rises (as during physical activity or exertion), perspiration begins, and the excess heat is removed by vaporization. It is assumed that this avenue of heat loss is adequately controlled by the body and that the heat removed by vaporization does not exceed the additional heat produced by the physical activity.

Additional heat is lost from the body through conduction to cold objects or surfaces with which it is in contact and in breathing cold air which results in the loss of heat from the lungs.

The index, therefore, does not provide a measure of the total possible loss from the body, but does give a good measure of the convective cooling, which is the major source of body heat loss.

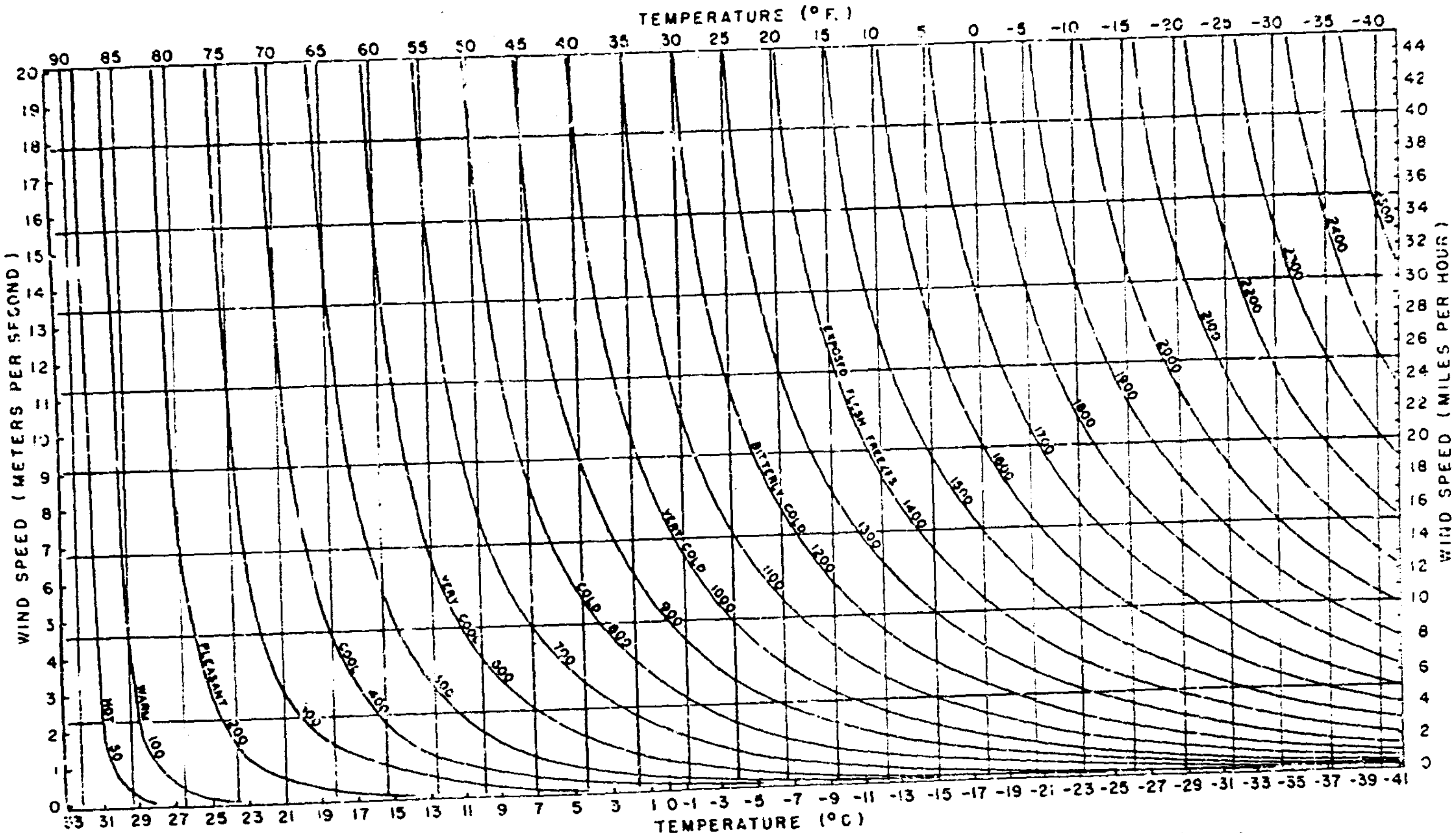
[illegible]. Aids for Computation of Windchill

Windchill Computation Tables

Tables I and II provide an easy means of computing instantaneous [illegible] mean windchill values from temperature in degrees Fahrenheit and wind speed in miles per hour, thus eliminating tedious conversion of these values from the English system to the metric system of units in the formula.

Table I, Windchill Computation, Temperature Factor, lists factors for the differences between skin temperature and ambient air temperature for air temperatures from 90°F. to -105°F. (obtained by converting the temperature element of the formula, 33°C., to 50.78 -.(.56) °F.).

Table II, Windchill Computation, Wind Speed Factor, lists heat loss factors in Kg.Cals/m^2/hr for each tenth of a mile per hour from 0 to 20 mph and by one mile per hour units from 20 to 45 mph. For wind speed over 45 mph, Siple recommends a maximum cooling rate of 35 Kg.Cals/m^2/hr. Factors for applicable values of ambient air temperature and wind speed, when multiplied together, result in the windchill index in Kg.Cals/m^2/hr. For example, the factors for a wind speed of 20 mph and an air temperature of -30°F. are given in Tables I and II as 31.35 and 67.58, respectively. Multiplication of these factors results in a windchill index of 2,118 Kg.Cals/m^2/hr.



SOURCE: Based on nomogram originally prepared by the Climatic Research Unit Office Of The Quartermaster General, January 1943.

Figure 1: Windchill Nomogram

TABLE I: Windchill Computation, Temperature Factor

Values derived from the temperature component of the windchill formula, converted from the metric (33 - °C.) to (50.78 -(.56)°F.). To obtain windchill index in Kg.Cals./m^2/hr., multiply temperature factor with appropriate wind factor from Table II.

°F.	Factor	°F.	Factor	°F.	Factor	°F.	Factor
90	.78	41	27.82	-8	55.26	-57	82.70
89	1.34	40	28.38	-9	55.82	-58	83.26
88	1.89	39	28.94	-10	56.38	-59	83.82
87	2.45	38	29.50	-11	56.94	-60	84.38
86	3.00	37	30.06	-12	57.50	-61	84.94
85	3.56	36	30.62	-13	58.06	-62	85.50
84	4.11	35	31.18	-14	58.62	-63	86.06
83	4.67	34	31.74	-15	59.18	-64	86.62
82	5.22	33	32.30	-16	59.74	-65	87.18
81	5.77	32	32.86	-17	60.30	-66	87.74
80	6.33	31	33.42	-18	60.86	-67	88.30
79	6.54	30	33.98	-19	61.42	-68	88.86
78	7.10	29	34.54	-20	61.98	-69	89.42
77	7.66	28	35.10	-21	62.54	-70	89.98
76	8.22	27	35.66	-22	63.10	-71	90.54
75	8.78	26	36.22	-23	63.66	-72	91.10
74	9.34	25	36.78	-24	64.22	-73	91.66
73	9.90	24	37.34	-25	64.78	-74	92.20
72	10.46	23	37.90	-26	65.34	-75	92.78
71	11.02	22	38.46	-27	65.70	-76	93.34
70	11.58	21	39.02	-28	66.46	-77	93.90
69	12.14	20	39.58	-29	67.02	-78	94.46
68	12.70	19	40.14	-30	67.58	-79	95.02
67	13.26	18	40.70	-31	68.14	-80	95.58
66	13.82	17	41.26	-32	68.70	-81	96.14
65	14.38	16	41.82	-33	69.26	-82	96.70
64	14.94	15	42.38	-34	69.82	-83	97.26
63	15.50	14	42.94	-35	70.38	-84	97.82
62	16.06	13	43.50	-36	70.94	-85	98.38
61	16.62	12	44.02	-37	71.50	-86	98.94
60	17.18	11	44.62	-38	72.06	-87	99.50
59	17.74	10	45.18	-39	72.62	-88	100.06
58	18.30	9	45.74	-40	73.18	-89	100.62
57	18.86	8	46.30	-41	73.74	-90	101.18
56	19.42	7	46.86	-42	74.30	-91	101.74
55	19.98	6	47.42	-43	74.86	-92	102.30
54	20.54	5	47.98	-44	75.42	-93	102.86
53	21.10	4	48.54	-45	75.98	-94	103.42
52	21.66	3	49.10	-46	76.54	-95	103.98
51	22.22	2	49.64	-47	77.10	-96	104.54
50	22.78	1	50.22	-48	77.66	-97	105.10
49	23.34	0	50.78	-49	78.22	-98	105.66
48	23.90	-1	51.34	-50	78.78	-99	106.22
47	24.46	-2	51.90	-51	79.34	-100	106.78
46	25.02	-3	52.46	-52	79.90	-101	107.34
45	25.58	-4	53.02	-53	80.46	-102	107.90
44	26.14	-5	53.58	-54	81.02	-103	108.46
43	26.70	-6	54.14	-55	81.58	-104	109.02
42	27.26	-7	54.70	-56	82.14	-105	109.58

[illegible] Wind Speed Factor

Values [illegible] of the windchill formula [illegible] from wind speed in meters per second to wind speed [illegible] hour.

mph	Factor	mph	Factor	mph	Factor	mph	Factor	mph	Factor
.0	[illegible].45	[illegible]	[illegible]	[illegible]	[illegible]	14.1	29.19	18.8	31.02
.1	[illegible].54	[illegible]	[illegible]	[illegible]	[illegible]	14.2	29.28	18.9	31.05
.2	[illegible].27	[illegible]	[illegible]	[illegible]	[illegible]	14.3	29.30	19.0	31.07
.3	[illegible].99	[illegible]	[illegible]	[illegible]	26.96	14.4	29.33	19.1	31.09
.4	[illegible].18	[illegible]	[illegible]	[illegible]	26.98	14.5	29.41	19.2	31.11
.5	[illegible].97	[illegible]	[illegible]	[illegible]	27.07	14.6	29.44	19.3	31.13
.6	15.33	[illegible]	[illegible]	[illegible]	27.16	14.7	29.46	19.4	31.16
.7	[illegible].75	[illegible]	[illegible]	[illegible]	27.18	14.8	29.55	19.5	31.24
.8	16.04	[illegible]	[illegible]	[illegible]	27.20	14.9	29.57	19.6	31.26
.9	16.40	[illegible]	[illegible]	[illegible]	27.29	15.0	29.59	19.7	31.29
1.0	16.69	[illegible]	[illegible]	[illegible]	27.31	15.1	29.68	19.8	31.31
1.1	16.97	[illegible]	[illegible]	[illegible]	27.40	15.2	29.70	19.9	31.33
1.2	17.26	[illegible]	[illegible]	[illegible]	27.49	15.3	29.72	20.0	31.35
1.3	17.49	6.0	[illegible]	[illegible]	27.51	15.4	29.74	21	31.64
1.4	17.71	6.1	[illegible]	10.8	27.60	15.5	29.83	22	31.93
1.5	17.93	6.2	[illegible]	10.9	27.62	15.6	29.86	23	32.21
1.6	18.16	6.3	[illegible]	11.0	27.71	15.7	29.88	24	32.43
1.7	18.38	6.4	[illegible]	11.1	27.73	15.8	29.90	25	32.65
1.8	18.60	6.5	24.58	11.2	27.82	15.9	29.99	26	32.87
1.9	18.82	6.6	[illegible]	11.3	27.84	16.0	30.01	27	33.09
2.0	18.98	6.7	[illegible]	11.4	27.93	16.1	30.03	28	33.24
2.1	19.21	6.8	24.85	11.5	27.95	16.2	30.05	29	33.46
2.2	19.36	6.9	24.94	11.6	28.04	16.3	30.14	30	33.61
2.3	19.58	7.0	25.03	11.7	28.06	16.4	30.16	31	33.76
2.4	19.74	7.1	[illegible]	11.8	28.15	16.5	30.19	32	33.92
2.5	19.90	7.2	25.11	11.9	28.18	16.6	30.21	33	34.00
2.6	20.05	7.3	25.23	12.0	28.20	16.7	30.30	34	34.15
2.7	20.20	7.4	25.32	12.1	28.29	16.8	30.32	35	34.30
2.8	20.36	7.5	25.41	12.2	28.31	16.9	30.34	36	34.39
2.9	20.52	7.6	25.49	12.3	28.40	17.0	30.36	37	34.48
3.0	20.67	7.7	25.52	12.4	28.42	17.1	30.45	38	34.56
3.1	20.83	7.8	25.61	12.5	28.51	17.2	30.47	39	34.65
3.2	20.99	7.9	25.69	12.6	28.53	17.3	30.50	40	34.73
3.3	21.14	8.0	25.78	12.7	28.55	17.4	30.52	41	34.82
3.4	21.23	8.1	25.87	12.8	28.64	17.5	30.54	42	34.90
3.5	21.39	8.2	25.89	12.9	28.66	17.6	30.63	43	34.98
3.6	21.54	8.3	25.98	13.0	28.75	17.7	30.65	44	35.00
3.7	21.63	8.4	26.07	13.1	28.77	17.8	30.67	45	35.09
3.8	21.79	8.5	26.16	13.2	28.79	17.9	30.69		
3.9	21.87	8.6	26.18	13.3	28.85	18.0	30.72		
4.0	22.03	8.7	26.27	13.4	28.91	18.1	30.74		
4.1	22.12	8.8	26.36	13.5	28.93	18.2	30.83		
4.2	22.27	8.9	26.38	13.6	29.02	18.3	30.85		
4.3	22.36	9.0	26.47	13.7	29.04	18.4	30.87		
4.4	22.52	9.1	26.56	13.8	29.06	18.5	30.89		
4.5	22.61	9.2	26.58	13.9	29.15	18.6	30.91		
4.6	22.70	9.3	26.67	14.0	29.17	18.7	30.94		

Windchill Nomogram

Rapid approximations of the windchill index for windspeed from 0 to 45 mph and temperature from 92° to -43°F. may be obtained from the Windchill Nomogram, Figure 1. When the windchill index is less than the rate of body heat production, excess heat is removed by vaporization. Under conditions of bright sunshine, indicated values of the windchill index should be reduced by about 200 Kg. Cals. Expressions of relative comfort indicated on the nomogram are based upon an individual in a state of inactivity.

3. Windchill — Comfort Relationships

Some success has been attained in relating windchill to comfort, in spite of the many variables that make one person feel comfortable when another is not. The outstanding variables affecting any scale or measure of comfort are the physiological and psychological differences among individuals and the degree of acclimatization and physical activity.

Dr. Siple correlated atmospheric cooling with human comfort and lower limits of physical endurance. During his experiments in the Antarctic, relative comfort observations were obtained simultaneously with his measurements of atmospheric cooling. Table III gives a summary of the general bioclimatic responses at windchills from 600 to 2,300 Kg.Cal./m^2/hr.

TABLE III

Stages of Relative Human Comfort and Environmental Effects of Atmospheric Cooling (After Siple,(9) 1945)

Windchill (Kg.Cal./m^2/hr.)	
600	Considered as comfortable when dressed in wool underwear, socks, mitts, ski boots, ski headband, and thin cotton windbreaker suits, and while skiing over level snow at about 3 mph. (Metabolic output about 200 Kg.Cal./m^2/hr.)
1,000	Considered unpleasant for travel on foggy and overcast days.
1,200	Considered unpleasant for travel on clear sunlit days.
1,400	Freezing of exposed human flesh begins, depending upon degree of activity, amount of solar radiation, character of skin, and circulation. Travel or living in temporary shelter becomes disagreeable.
2,000	Travel or living in temporary shelter becomes dangerous. Exposed areas of flesh will freeze within less than 1 minute for the average individual.
2,300	Exposed areas of flesh will freeze within less than ½ minute for the average individual.

Gold[8] proposed a set of descriptive terms for comfort at temperatures between 30° and 90°F. at wind speeds of 5, 15, and 25 miles per hour under varying conditions of cloudiness. Table IV, in which these terms are presented, also includes windchill values appropriate to the temperature and wind conditions described. The windchill values were obtained by multiplying applicable factors for temperature and wind speed from Tables I and II.

Table IV shows that under identical temperature and wind conditions, subjective response of individuals varies with the amount of solar radiation, indicating that some heat is being provided by the radiation. In bright sunshine, a person may feel "very cool" at a windchill of 840 Kg.Cal./m^2/hr. (wind speed 15 mph at 40°F.), but with radiation reduced by a thick cloud cover, the subjective response to the same windchill is indicated as "cold". To allow for the additional heat provided during periods of bright sunshine, the windchill index should be reduced by about 200 Kg.Cals./m^2/hr. With light cloud conditions, the index should be reduced by about 100 Kg.Cals./m^2/hr.

TABLE IV: Descriptive Terms with Windchill Values Appropriate to Different Temperatures and Wind Speeds*

Wind Speed (mph)	Temp. (°F.)	Wind-chill	In Sunshine	Light Cloud	Thick Cloud
5	90	18	Unbearably hot	Unbearably hot	Very warm
	80	146	Unbearably hot	Very warm	Warm
	70	269	Hot	Warm	Pleasant
	60	398	Warm	Pleasant	Pleasant
	50	526	Pleasant	Cool	Cool
	40	658	Cool	Cool	Very cool
	30	788	Cool	Very cool	Cold
15	90	23	Unbearably hot	Very warm	Very warm
	80	187	Hot	Warm	Pleasant
	70	343	Warm	Pleasant	Cool
	60	508	Pleasant	Cool	Cool
	50	674	Cool	Very cool	Very cool
	40	840	Very cool	Cold	Cold
	30	1005	Cold	Very cold	Very cold
25	90	25	Unbearably hot	Very warm	Warm
	80	206	Very warm	Pleasant	Pleasant
	70	378	Pleasant	Cool	Cool
	60	561	Cool	Very cool	Very cool
	50	744	Very cool	Cold	Cold
	40	927	Cold	Very cold	Very cold
	30	1109	Very cold	Bitterly cold	Bitterly cold

*(Partly after Gold[8])

4. <u>Map of Mean Windchill in the Northern Hemisphere, Coldest Month</u>

The map of mean windchill distribution in the Northern Hemisphere, presented at the end of this report, was originally prepared to answer requests for maps depicting the effects of windchill specifically in: 1) reducing speed of human reaction, and 2) increasing the time necessary to complete tasks requiring manual dexterity. The request necessitated preparation of the windchill map included in this report; this is a new analysis of mean windchill in North America and Europe and what is believed to be the first analysis of mean windchill distribution in Asia.

The map is based on windchill values computed from mean temperature and mean wind speed during the coldest month at each station. The windchill formula applies best to simultaneous conditions of wind and temperature, but use of average monthly values gives only slightly different results.

It has been proposed by some investigators (4) that this difference can be considerable, and that determination of mean windchill at various stations should be based on individual hourly observations. These proposals are usually based on the common assumption that the lowest temperatures in any locality always occur with calms or very light winds and that the low windchill values during these calm conditions are not sufficiently reflected by the averages. However, examination of wind frequency data at numerous arctic and subarctic stations reveals that this assumption is not valid for a majority of locations, and that light to moderate winds (3 to 18 mph) occur even at temperatures near the lowest on record at each station. (5,6). Analysis of 10 years of January data from Fort Churchill, Canada, indicates that the windchill index resulting from the use of mean temperature and mean wind speed data for the period is only 1.9 percent greater than the value obtained by averaging 3,720 individual bi-hourly windchill values for the same period. It is likely that analysis of similar data from other stations should result in equally small differences. It is felt, therefore, that windchills based on mean monthly values are sufficiently representative to afford a satisfactory measure of the relative severity of combinations of wind and low temperature.

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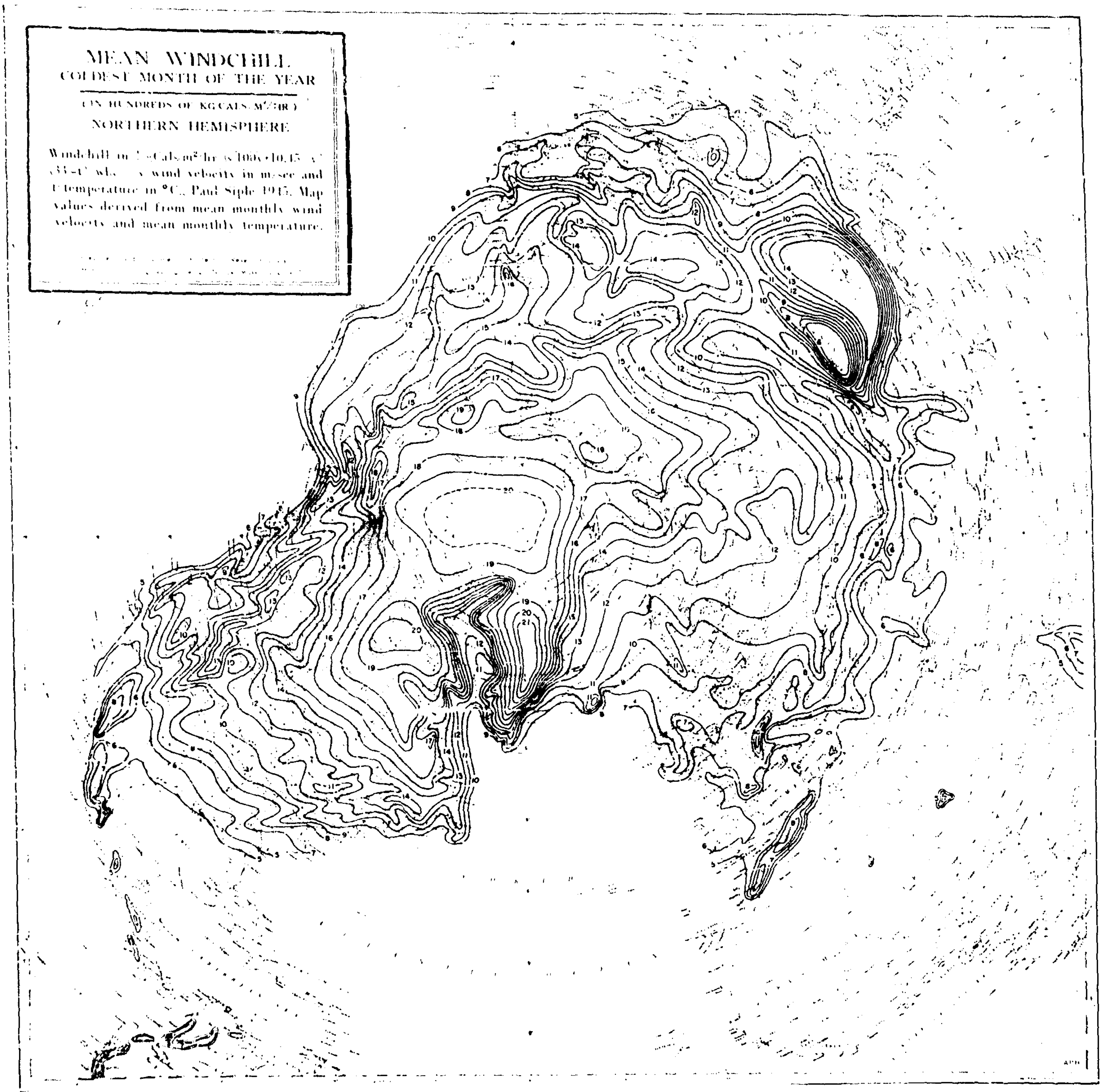
MEAN WINDCHILL
COLDEST MONTH OF THE YEAR
(IN HUNDREDS OF KG CALS/M²/HR)
NORTHERN HEMISPHERE
Windchill in Kg-Cals/m²/hr is (√100v + 10.45 − v)(33 − t) where v is wind velocity in m/sec and t temperature in °C., Paul Siple 1945. Map values derived from mean monthly wind velocity and mean monthly temperature.
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A map of the Northern Hemisphere shows the mean windchill distribution for the coldest month of the year, using isopleths at intervals of 100 units of windchill, from 500 to 2,100 Kg.Cals/m²/hr. Values were derived from monthly means of temperature and wind speed from more than 1,000 stations.

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